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Experimental investigation of modified solar still integrated with solar collector

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A R T I C L E I N F O

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A B S T R A C T

The limited productivity of traditional solar still considers as one of the most prominent obstacles to their implementation. Thus, the main objective of this study is to improve traditional solar still (TSS) productivity in two successive stages. In the first stage, a rotating hollow cylinder is used within the solar still to increase the surface area of evaporation and reduce the boundary layer thickness of untreated water film. Three rotational speeds have been tested (0.5, 1 and 3 rpm). The second stage included the integration of an external solar collector with the modified solar still (MSS) to raise the basin saltwater temperature. From the analysis of experimental results, it is observed that the productivity increased with decreasing rotational speed of a hollow cylinder and the maximum value obtained at the lower speed (0.5 rpm). Furthermore, integrating outer solar collector results in further enhancement, where the productivity of freshwater observed to be 5.5 L/m^2 for MSS compared to 1.4 L/m^2 from TSS. Accordingly, the productivity enhanced by 292% at an estimated cost to produce 1 L of freshwater of 0.048 $ and 0.049 $ from MSS and TSS respectively.

1. Introduction

Throughout the ages, solar energy is one of the most useful energies. By comparing solar energy with other energies, solar energy is clean, available, cheap and most importantly environmentally friendly. It is the most promising source to meet the challenges facing the whole world such as the increasing energy demand and water scarcity [1]. The freshwater scarcity is considered the main problem in the world which worsens with time, due to weather conditions changing and increasing population. Freshwater is available in civilized areas, while there is real suffering for drinking water in rural and remote areas. Furthermore, industrial development has increased the rate of drinking water pollution [2]. A solar water distillery is a simple equipment that produces freshwater from saline water and polluted water. Distillery technology consumes energy from sunlight without fuel consumption which will reduce global warming and greenhouse gas emissions problems [3]. The solar radiation heats and evaporates the basin water within solar still and separates it from dirt, salt and impurities and anything else. When water vapor temperature reduced, the latter returns to the liquid phase [4]. There are several parameters that positively or negatively affect the production of freshwater solar stills such as design, operational and environmental parameters. Researchers have been tried to improve solar distillate production through design and operational parameters because environmental parameters are difficult to control such as humidity, solar radiation intensity, ambient

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air temperature [5,6]. The most important target of those improvements is to enhance productivity through operational and design factors. An experimental study was conducted using parabolic dish collector assisted the triple basin solar still with cooling the solar still cover to enhance freshwater productivity [7]. The study includes four various cases; Triple basin solar alone, Triple basin solar with cooling cover, Triple basin solar integrated with a parabolic dish collector, and Triple basin solar integrated with a parabolic dish collector with cooling cover. The researchers found that case number four was the highest yield (around 16.94 kg/m^2/day). Another study [8], conducted to investigate the influence of using square and circular fins within single basin solar still. The authors found that daily productivity increases by about 36.7% and 26.3% for square and circular finned solar still respectively. On the other hand, thermal energy storage materials were used within solar still to save the thermal energy during sunrise hours and release it during shadow and evening hours to increase night production [9]. The study results showed that the used storage material such as paraffin wax in the basin solar still has led to reduce freshwater productivity during daytime by 7.4% and increase the output during night time. The highest daily production was 7.54 kg/m^2/day obtained with paraffin wax compared to 4.51 kg/m^2/day without paraffin wax in the basin solar still. Another experimental investigation on seawater distillation [10], was conducted using solar still with paraffin wax in the basin integrated with outer solar collector. From the results, it was observed that paraffin wax becomes more effective in the lower level of basin water, with the change in water level from 10 to 5 cm. The quantity of production doubled, also and the outer solar collector enhanced the freshwater productivity of the system. A theoretical investigation was conducted [11] to study the cooling of the solar still cover by passing water over. The water flow rate effects, water film cooling thickness, water film cooling temperature and wind speed have been investigated. The study concluded that the water film could improve the freshwater productivity about 8.2%, and this depends on different parameters of water-cooling film. The effects of using thermoelectric duct for cooling the solar still cover with the addition of copper oxide nanofluid in the modified solar still basin instead of saltwater has been studied [12]. The results showed that the use of thermoelectric cooling duct with adding 0.08% friction volume of the Cu_2O nanoparticles with the modified solar still basin led to significant improvement in the water productivity. The maximum values of productivity enhancement found to be about 81%, and optimal cost of freshwater productivity per liter found to be 0.0218 \$/L/m^2 for modified solar still. Numerical study has been carried out by integrating heat pump with solar still [13], to increases the temperature of basin water. The heat pump condenser was placed in the solar still basin water and the heat pump evaporator placed below the cover of solar still to increase the surface area of condensation. The results showed that the optimum daily freshwater productivity is 13.5 kg/m^2, at a higher rate of distillation by 75% compared with conventional solar still. Enhancing productivity of solar still by using rotating drum on shaft within the solar still has been investigated also [14]. Two types of solar still systems were adopted. The first amendment includes install a packet layer within the solar still in order to increase the freshwater productivity. The second amendment included utilization of a rotating shaft, installed in the basin water surface to disrupt the boundary layer of the basin, thus led to increases of water evaporation. The results showed that the efficiency for amended solar still increased by 5%, 6%, and 7.5% in May, June, and July respectively. Whereas by the shaft rotating (958 rpm) the PV scheme increased by 2.5%, 5%, and 5.5% in May, June, and July respectively. New hybrid design was presented [15] consisting of inclined solar still and wind turbine integrated with the main solar still. At various depths of water of 0.01, 0.02 and 0.03 m the system has been tested with two operational conditions (sun tracking and fixed to the south direction). The study results reveal that increasing the depth of basin water led to decrease in the freshwater productivity. The freshwater productivity from inclined solar still found to be higher than of main solar still by about 26.55 to 29.17% when the system towards the south. Furthermore, it was between 27.1 and 32.93% when system was tracking the sun. Another study [16] experimentally examine the increase of solar still productivity through the clothes wick rotated by a DC motor governed by a control circuit. When the DC motor is running, the clothes wick is submerged in water, while when the DC motor is off; wet clothes are exposed to sunlight. The results showed that the maximum thermal efficiency obtained for the run period of 30 s and stop period of 25 min; prove that when running a solar water distiller with a computer, it will reduce the cost of producing freshwater. Simple improvement study [17] was carried out included increasing the surface area of evaporation by installing a rotating-hollow drum within solar still. The new improved distillate products were evaluated in terms of economic and operational probability. The presented new design results in 200–300% increase in freshwater output. The researchers calculated the cost of the distillation of saltwater to estimate the system's probability in real market cost and this based on modified solar distiller and fuel. The results showed that the new distillation unit may cost less compared to other type of distillation apparatus. Enhanced distillery has been conducted [18,19], using a rotating-hollow cylinder inside solar still with an analytical study to evaluate performance. A theoretical analysis included governing equations, which has been resolved numerically and validated by experimental data. The hollow cylinder rotational speed was between 0.25 and 4 rpm. The study results showed that the cylinder speed inversely proportional to freshwater distillate. Furthermore, the modified solar still with hollow cylinder can cost less compared with other types of distiller's technology.

Thermal efficiency analysis and exergy were conducted [20] to estimating the productivity and performance of double slope solar still integrated with outer solar collector under forced circulation case. The study found that the daily thermal efficiency ranged between 13.55 to 31.07% and exergy efficiency ranged between 0.26 to 1.34%. An experimental investigation on seawater distillation [10], was conducted using solar still with paraffin wax in the basin integrated with an outer solar collector. From the results, it was observed that paraffin wax becomes more effective in the lower level of basin water, with the change in water level from 10 to 5 cm. The quantity of production doubled, also and the outer solar collector enhanced the freshwater productivity of the system.

From the review of previous studies, it is found that using inexpensive and available materials, such as the galvanized iron plate is a viable replacement for the costly aluminum used by previous researchers to form the hollow cylinder. Furthermore, it is possible to combine hollow cylindrical solar still and outer solar collector to increase basin water temperature. Therefore, the aim of current work is to obtain augmentation of production of freshwater by using a solar water distillation. This work is a ground-breaking attempt to introduce a hollow cylinder that slowly rotates within a solar water unit and integrated with outer solar collector. In current study the productivity of conventional solar still has been investigated after enhancement using rotating hollow cylinder made of corrosion-

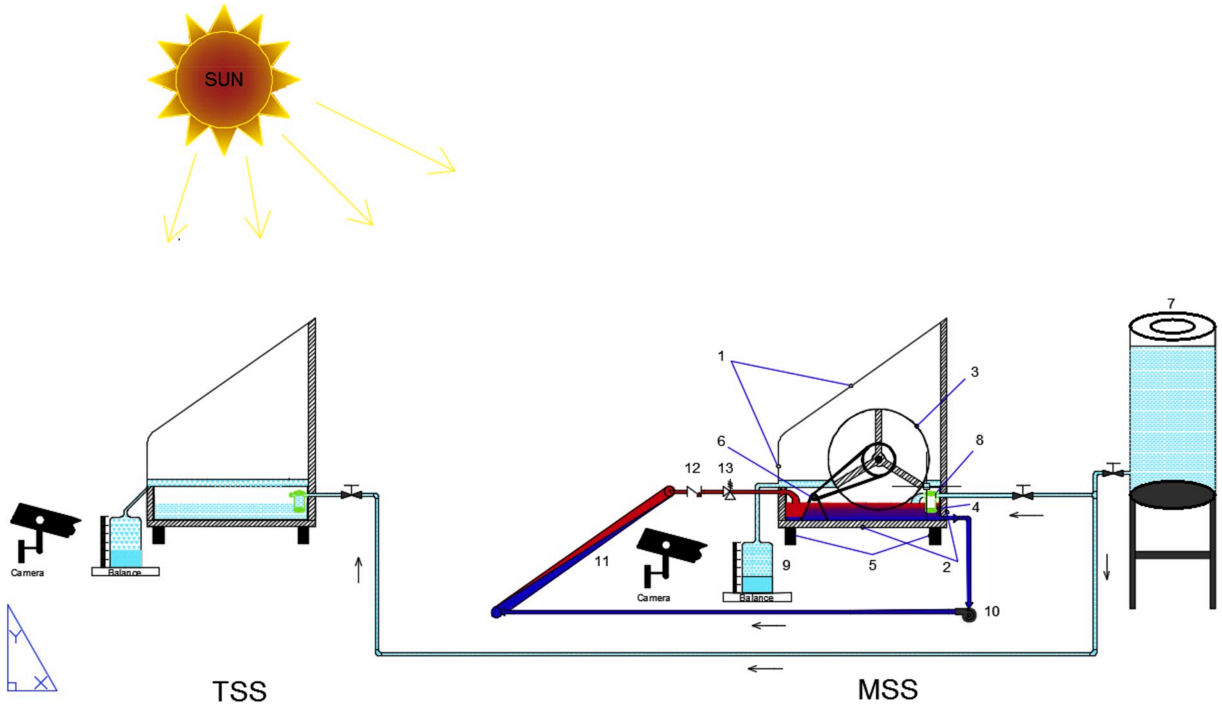

Fig. 1. Schematic diagram of the experimental station. TSS and MSS, 1- Plexiglas; 2- MDF; 3- Hollow drum; 4- Water basin; 5- Base; 6- 12V-DC Motor; 7- Feed water tank; 8- Mechanical floater; 9- Purified water tank; 10- Water pump; 11- Solar collector; 12- Check valve; 13- Safety valve.

resistant galvanized iron. In order to know the effect of hollow cylinder rotational speed on the performance and productivity of the modified solar still (MSS), three different speeds of hollow drum were tested (0.5, 1, and 3 rpm). After selecting the optimum speed for the better performance of the modified solar still, the MSS combined with an external solar collector to raise the basin saltwater temperature under the hollow cylinder and improve the freshwater productivity of modified solar still.

2. Experimental methodology

2.1. Solar Still and test rig

A schematic diagram is shown in Fig. 1 for the two types of single slope solar stills. The first type is a traditional solar still (TSS) and the second type is new modified solar still (MSS) with a rotating cylinder according to the previous study [18]. The surface area of basin water for both solar stills was 0.5 m^2 with dimensions of solar stills structure of 100 × 50 x 61.8 × 26.6 cm for length, width, big side height and small side height respectively. The solar still consists of a frame (wooden MDF) with dimensions of 100 × 50 x 10 × 1.8 cm for length, width, height and thickness respectively. The cover of solar stills made of transparent Plexiglas [21], of dimensions 100 × 50 x 50 × 14.8 cm for length, width, big side height and small side height respectively with single slope of 35° instilled on the frame. The Plexiglas cover fixed on the wooden frame by an aluminum channel to collect water droplets condensed on the inner surface of the Plexiglas cover. The distilled water then passes through the aluminum channel to a plastic water tank at the bottom of solar still. All parts are fixed with silicone glue to prevent air leakage. The water basin (94 × 46 × 10 cm for length, width, height respectively) made of galvanized iron plate and coated with black colour to absorb a maximum amount of solar radiation. Galvanized iron sheet of 100 × 100 × 0.06 cm for length, width, thickness and thickness respectively has been used to fabricate the hollow cylinder and coated with a black colour to absorb a maximum amount of solar energy. The hollow cylinder installed on a low carbon steel shaft of 0.8 cm diameter and 95 cm length with 0.8 cm bearings on the two ends of the shaft. A small DC motor of 12 V and 0.1 A, which used to move car's windows, has been used to rotate the hollow cylinder. A photocell panel 30 Watts has been used to supply DC motor with electrical power during the daytime and connected to a storage battery to operate during shadow times. To control and adjust the rotational speed of the DC motor, the motor is integrated with speed regulator type PWM motor speed controller switch. A feedwater tank (50 cm diameter x 100 cm height) has been used to supply solar stills with untreated water using a globe valve to control the flow rate of feed water to both types of solar stills. A mechanical floater has been used at the basin of solar stills to maintain the water level during the operation period of solar stills. To clean and drain the basin liner from salts and calcification sand, a hole was made at the bottom of the basin in which globe valve was installed. The TSS formed of the mentioned above but without a hollow cylinder.

The MSS was integrated with external solar collector as shown in Fig. 1, the inner bottom surface of the solar collector was made of galvanized steel plate and coated with a black color in order to increase the ability to absorb solar energy, dimension of galvanized steel

Table 1
Accuracy of different experimental devices.

No	Type device	accuracy
1	SD data logger (model 88598)	$\pm$ 0.3% $rdg + 1^{\circ}C$
2	Digital laser infrared thermometer temperature (model TEGMART TE-TEM-LS-PRB).	$\pm$ 1.5%
3	Humidity and temperature meter (model GM1362)	Humidity 3% Temperature 0.5%
4	Solar power meter device (model TENMARS TM-207)	$\pm 10\ W/m^2$
5	Anemometer device (model ut363)	$\pm$5% $rdg + 0.5^{\circ}C$

110 cm length, 90 cm width and 0.01 cm thickness, with a surface area of 9900 cm^2. A 30 copper tubes laid on the black steel plate with a diameter of 1.6 cm and 2.5 cm space between each two consecution pipes and covered with double glass cover 4 mm thickness. Sunlight passes through the glass to raise the black steel plate temperature, and at the same time reduce the thermal losses emitted by the absorber plate. The water circulates from the inlet solar header to the outlet header which is made of copper pipe with 4.2 cm diameter, through 30 copper tubes. A cover casing is a box made of a wooden frame to hold all the above elements. The box dimension 120 cm width, 100 cm length and 10 cm depth, the surface area of collector 1200 cm^2. The solar collector inclined by 35° from horizon. The water circulates between the MSS and the solar collector tubes in an open-loop by natural or forced convection through a 12 V DC water pump with rate of power consumption 10 W with maximum water flow rate of about 1.2 L/min [22].

2.2. Parameter Identification and measurement

Various parameters affect the solar still performance, such as operating, design and environmental parameters, these parameters have positive or negative effects on the performance of solar stills. In the current study, the main parameter affects the productivity of enhanced solar still is the rotational speed of hollow cylinder RSHC which should be investigated for better productivity [19]. The high RSHC may affect the evaporation rate of the thin film water on the cylinder surface, on the other hand, if the RSHC is too low it may lead to evaporate the water film faster. This can lead to dry the cylinder surface, because of the high temperature of drum surface during sunrise.Moreover, the very low RSHC means that the system requires special equipment such as gearbox and electric motor with high torque to overcome the weight of the drum beside and the weight of water in the water basin, thereby increasing the cost of freshwater productivity. In the current study, a small, low-cost, lightweight, easy-to-install DC motor with RSHC 0.5,1 and 3 rpm has been used to investigate the daily production rate. The motor speed was controlled using a speed regulator switch.

Another important parameter that directly affects the performance of modified solar still is the basin water temperature. During the experiments, it was observed that the water temperature under the hollow cylinder was lower than in the conventional still. Therefore, to solve this problem, external solar collector was integrated with MSS to increase the basin water temperature.

To assess the effect of different parameters on the solar stills system performance, various devices have been used to measure these parameters. SD data logger 4 channels and K-thermocouple device (model 88598) with thermocouples K-type 0.3 mm diameter have been used in this study. The thermocouples were calibrated between 0 and 100 °C and used to measure the temperatures at different points of the solar still. The measured temperatures include; saltwater basin temperature, basin liner temperature, vapor temperature within solar still and inside and outside Plexiglas cover temperature. A digital laser infrared thermometer temperature (model TEGMART TE-TEM-LS-PRB) has been used to measure the outer surface temperature of the rotating hollow cylinder. Anemometer device (UT363) has been used to measure the surrounding wind speed. A solar power meter device (TENMARS TM-207) in W/m^2 units used to measure solar radiation values throughout the day. Humidity and temperature meter (GM1362) have been used and fixed in the shade to protect from the sun radiation at height of 1 m from the surface ground to measure the temperature and relative humidity of the ambient air. Table 1 presents thr accuracy of different experimental devices used in this study.

2.3. Experimental procedures

The experimental investigation carried out at the Ural Federal University during the months of June, July, August, and September 2019 according to Ekaterinburg/Russia city climate (Latitude 56.84 °N, Longitude 60.58 °E), in which the system directed to the south direction. All tests started at 08:00 a.m. and ended at 08:00 p.m. for different days, before starting the test Plexiglas cover has been cleaned and the water level ensures within the basin at 4 cm. Measurements have been recorded for every 30 min throughout the day. All measuring instruments have been set up and equipped to measure the different investigated parameters. The tested parameters include; temperatures of Plexiglas cover, metal basin, brine water, relative humidity within solar stills, solar radiation intensity, wind speed, temperature and relative humidity of ambient air. The study was conducted over four months with variable environmental conditions such as solar radiation intensity, ambient temperature and relative humidity. In addition, the time of sunrise and sunset ranging from 04:10 a.m. to 09:50 p.m. in Jun, from 04:20 a.m. to 09:40 p.m. in July, from 05:20 a.m. to 08:40 p.m. in August and from 06:20 a.m. to 07:20 p.m. in September.

The current study included two stages, in the first stage; the effect of hollow cylinder rotational speed on the performance of solar still has been investigated. The second stage has included the effect of adding external solar collector to the distillate system on thermal performance at an optimum rotational speed.

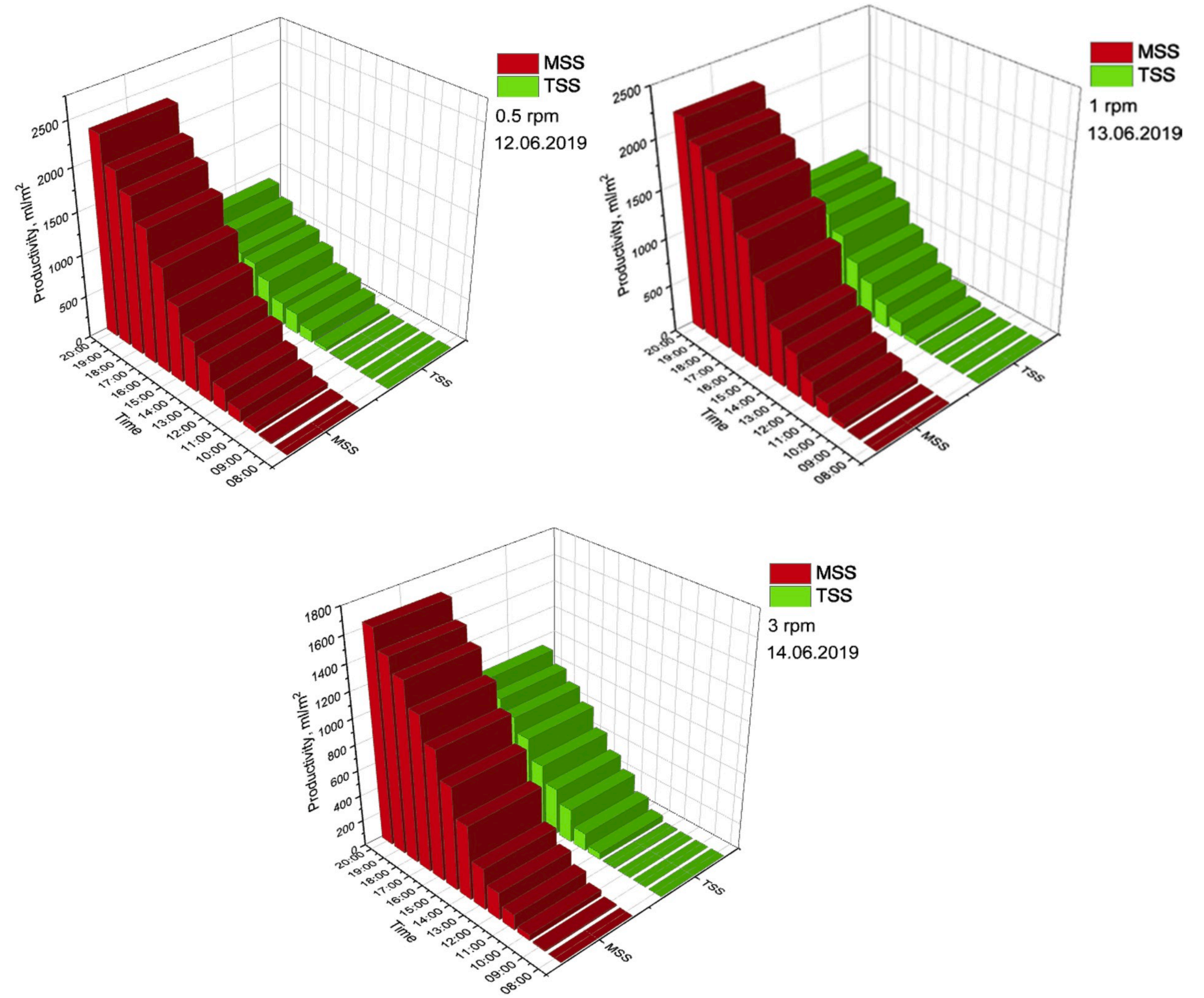

Fig. 2. The relation between the time for and productivity for MSS and TSS at various rotational speeds of 0.5, 1 and 3 rpm.

3. Results and discussion

The impact of operating parameters such as the rotational speed of hollow cylinder, integrating outer solar collector with MSS and productivity has been investigated in this study. The obtained results were collected and analyzed to compare the performance and discuss the effect of each parameter on the enhancement in the overall freshwater produced in terms of the fabricating cost.

3.1. Productivity rate

In order to investigate the impact of the rotational speed of hollow cylinder on productivity, tests have been conducted at different rotational speeds of 0.5, 1 and 3 rpm, for several different days during four months of 2019 at different environmental conditions.

From Fig. 2 it can be observed that the freshwater productivity ratio of the MSS is more than that of the TSS for a perfect day in June 2019. Two main important reasons for productivity enhancement of MSS, first one the thin water boundary layer which formed over the drum surface that leads to a high rate of evaporation compared with TSS. The second reason is the increase in the surface area of evaporation section in MSS, which constantly renewed in comparison with the TSS. The surface area in MSS was 2.538 m^2, which equals to about five times the surface area in TSS ($0.5\ m^2$). It can be seen also from Fig. 2 that the productivity of the MSS with 0.5, 1 and 3 rpm started early in comparison with TSS, to exceed the productivity of TSS several times until 10:30 a.m. Afternoon it is reduced to reach 161% with 0.5 rpm, 111% with 1 rpm and 75% with 3 rpm at 08:00 p.m. The reason for the significant enhancement in MSS productivity before 10:30 a.m. is that the solar radiation directly heats the hollow cylinder surface. Thus the thin water film adjacent to the surface of the cylinder evaporates. While in the TSS, the solar radiation directly reaches the basin water, therefore, the latter takes a longer time to reach the evaporation state. The main reason for this disparity in the rate of improvement in productivity at 0.5 rpm,

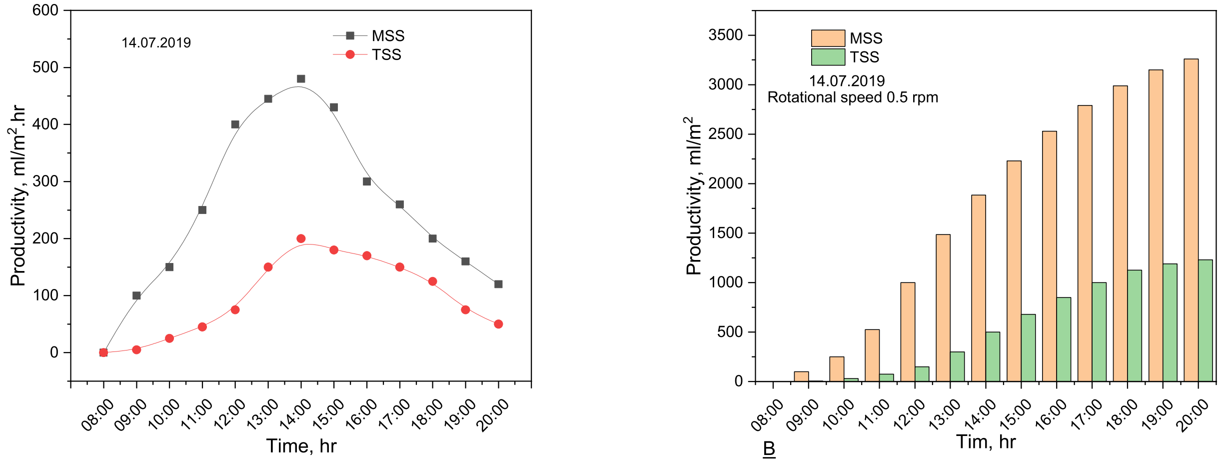

Fig. 3. A- The productivity of freshwater for each hour of MSS at rotation speed 0.5 rpm and from TSS. B- Accumulated yield of freshwater from MSS at 0.5 rpm and TSS.

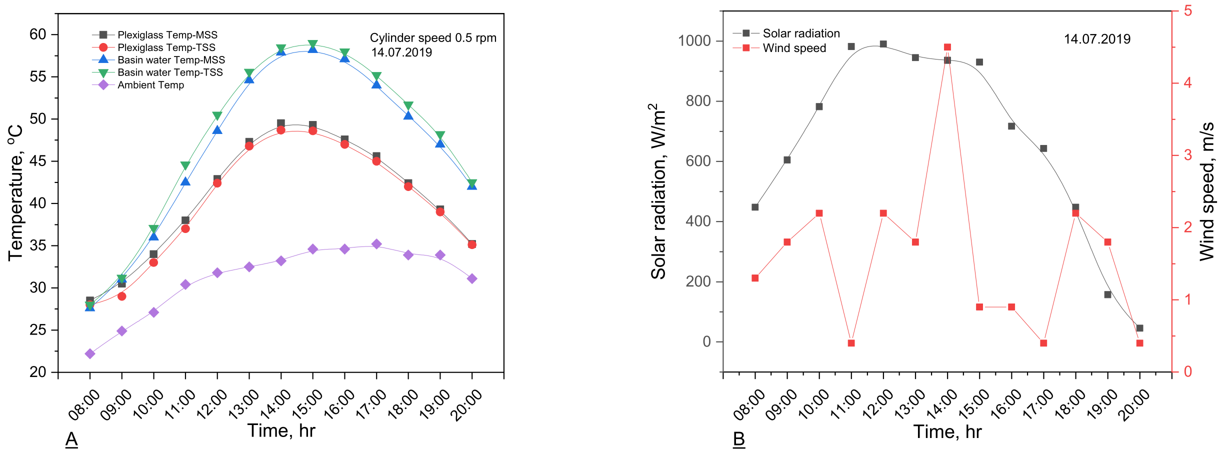

Fig. 4. A- Hourly temperatures of Plexiglas and basin water for each hour of MSS at cylinder speed 0.5 rpm and TSS. B- Hourly wind speed and solar radiation for MSS and TSS.

because the boundary water film on the drum surface has enough time to evaporate, while at rotational speed 1 and 3 rpm, they have less time to evaporate [19]. The enhancement appeared in throughout the day in MSS, due to the increased evaporation rate of the water film layer during sunrise. Relation 1 illustrated the mechanism of heat transfer by convection q_{dp} from each element i of the n elements of drum surface with width of dx and length L_d (m).

$$q_{dp} = \sum_{i=1}^{n} dx.L_d.h_{dp}.\,(T_d - T_{gi}). \tag{1}$$

Where: h_{dp}: Coefficient of heat transfer by convection from drum surface to inside Plexiglas surface, $\frac{W}{m^2}.°C$, T_d: drum temperature (°C) and T_{gi} it is inside Plexiglas temperature (°C).

$$dx = \frac{2\pi.R.dt}{60.N_d}. \tag{2}$$

R is the drum radius, dt is the increment of time (s) and N_d is the rotational speed of the drum (rpm).

Consequently, the heat energy transferred by free convection from the hollow cylinder surface to the inner surface of the Plexiglas directly depends on the rotational speed.

3.2. Modified solar still integrated with outer solar collector

The experimental results show that the best improvement ratio of freshwater productivity was at 0.5 rpm. In July 2019 the same

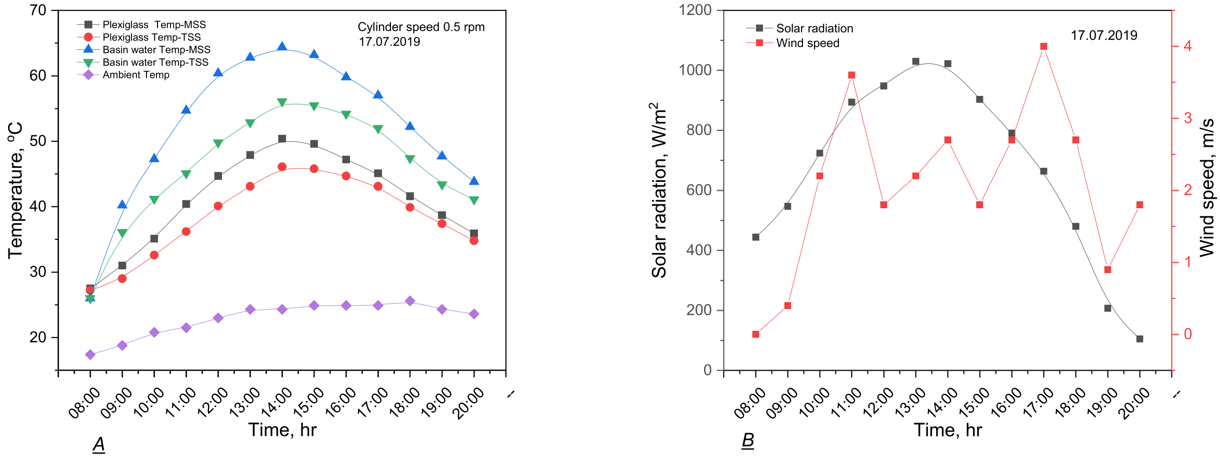

Fig. 5. A- Hourly temperatures of Plexiglas and basin water for each hour of MSS with solar collector at cylinder speed 0.5 rpm and TSS. B- Hourly wind speed and solar radiation for MSS and TSS.

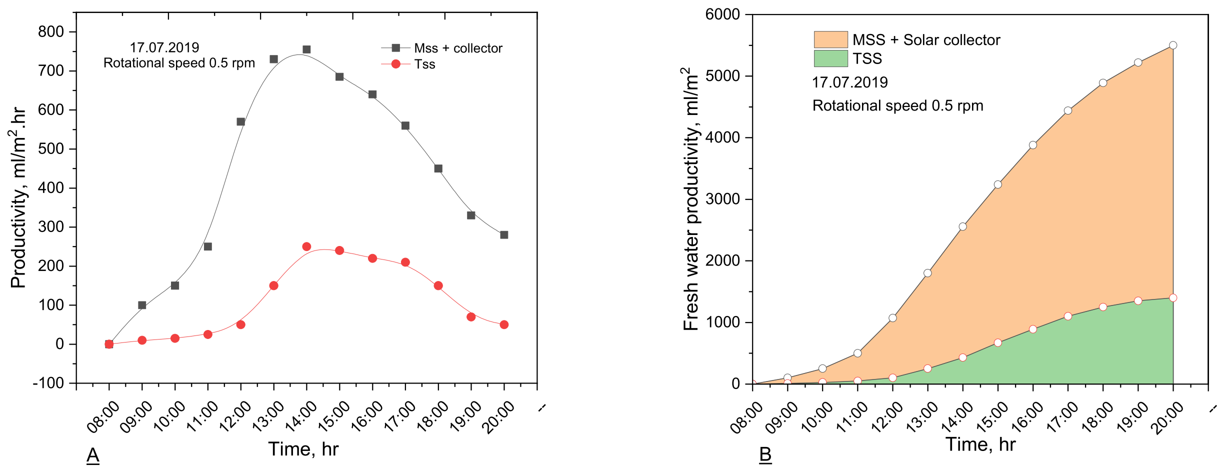

Fig. 6. A- The productivity of freshwater for each hour of MSS with solar collector at rotation speed 0.5 rpm and for TSS. B- Accumulated yield of freshwater from MSS with solar collector at 0.5 rpm and TSS.

thermal behavior observed but with an improvement rate of 165% at 0.5 rpm of MSS with an increase in the amount of freshwater production by about 1240 ml/m^2 from TSS and 3260 ml/m^2 from MSS as shown in Fig. 3-B. The maximum freshwater productivity per hour of MSS and TSS found to be about 480 and 200 ml, respectively, at 02:00 p.m. as shown in Fig. 3-A. The value of solar radiation was 936 w/m^2, ambient temperature 33.2 °C and wind speed 4.5 m/s as shown in Fig. 4-B. The reason for the increase in the quantity of freshwater production in July is due to the change in environmental conditions such as solar radiation, ambient temperature and wind speed. However, it is observed that the basin water temperature within the MSS was lower than that of the TSS by about 0–2.5 °C. This reduction because the solar radiation doesn't reach the water surface under the hollow cylinder as shown in Fig. 4-A. Although the hollow cylinder blocks solar radiation, the basin water heated by cylinder (as heat source) and by the solar radiation which reaches a part of the basin water about 0.092 m^2. The highest amount of evaporation occurs from a thin water film layer inside and outside cylinder surface. This justifies the reason for integrating external solar energy with MSS in order to raise the temperature of basin water. The heat and mass transfer processes inside MSS occur by four mechanisms: convection, radiation, evaporation and conduction in the cylinder plate.

To overcome this problem an external solar collector has been integrated with MSS at a rotational speed of 0.5 rpm. From Fig. 5-A, it is observed that, integrating solar collector with the MSS lead to raise the temperature of the water under the hollow cylinder by about 0–10.5 °C more than in the TSS which increase the evaporation rate of MSS [23]. Therefore, the Plexiglas cover temperature in MSS increased by about 0.3 to 5.1 °C in comparison with Plexiglas cover in TSS. From Fig. 5-A, it is observed that the highest basin water temperature of the MSS and TSS found to be 64.2 °C and 56.1 °C respectively at 02:00 p.m. While Plexiglas temperature of the MSS and TSS found to be 50.4 °C and 46.1 °C respectively at 02:00 p.m. when the value of solar radiation was at its peak (1022 w/m^2) and wind speed 2.7 m/s as shown in Fig. 5-B.

Table 2
Fabrication fixed cost for MSS and TSS.

Unit	Quality	Cost of TSS, $	Cost MSS, $
MDF wooden board, 1.8 cm	2 m^2	14	14
Plexiglas cover 0.3 cm thickness	1.2 m^2	15	15
Galvanized iron sheet basin, 0.08 cm	1.5 m^2	11	11
Galvanized iron sheet drum, 0.06 cm	1 m^2	–	6
DC- motor 12 V + regulator	1 piece	–	7
Photovoltaic system	2 pieces	–	100
Battery + Pump	1 piece	–	30
Solar Collector + Accessories	1 piece	–	100
Spray paint heat-resistant	2 pieces	3	3
A mechanical float	1 piece	1	1
Heat-resistant silicone glue	2 pieces	3	3
Saltwater feeding system	–	15	15
Other	–	20	10
Total cost	–	82	315

From Fig. 6-A it is observed that the maximum freshwater productivity per hour of MSS and TSS at 0.5 rpm rotational speed found to be about 755 and 250 ml, respectively, at 02:00 p.m. The freshwater productivity of MSS integrated with the solar collector is higher than the MSS without solar collector at the same rotational speed 0.5 rpm. Thus, at rotational hollow cylinder speed 0.5 rpm the MSS integrated with the outer solar collector has a higher distillation output than that of conventional solar distillation. The cumulative daily yield of the MSS with solar collector and TSS found to be 5500 ml/m^2 and 1400 ml/m^2 respectively, with an improvement rate of 292%. Also, the daily yield of the MSS with solar collector was higher than the MSS without solar collector at the same rotation speed of 0.5 rpm as shown in Fig. 6-B.

4. Estimate distillers' cost

The production cost of 1 L of freshwater for a perfect day (17.07.2019) at the highest productivity improvement with a rotational speed of 0.5 rpm estimated as follows:

The total cost of the fabrication of solar still C is equal to summing the fixed (fabrication) costs F and operation (variable) cost V [24]:

$$C = F + V. \tag{3}$$

Where

$$V = n \times 0.1 \times F. \tag{4}$$

Suppose the variable cost V is 0.05 F per year, n: Life expectancy for both solar stills are 10 years.

Then the total cost from Table 2 for TSS

$$C = 82 + 10 \times 0.05 \times 82 = 123\ \$$$

For MSS

$$C = 315 + 10 \times 0.05 \times 315 = 472.5\ \$$$

The daily productivity from TSS per unit area 0.5 m^2 was 1.4 L/m^2 and for MSS 5.5 L/m^2. If assuming both solar stills operating 180 days in the year, the total annual productivity during the work period 10 years for TSS is 2520 L, and for ESS is 9900 L. So, the cost of production of one littler of freshwater from TSS is 123/2520 = 0.0488$ and from MSS is 472.5/9900 = 0.0477 $.

5. Conclusion

According to what has been reviewed and discussed during the analysis of the results, the following conclusion can be addressed;

1. Modified solar still MSS productivity significantly increased compared to TSS.
2. Decreasing the number of revolutions per minute of the rotating hollow cylinder within the modified solar still from 3 rpm to 0.5 rpm accelerates the rate of saltwater evaporation and increases the rate of freshwater production from1.650 L/m^2 to 2.350 L/m^2.
3. The highest improvement ratio in freshwater productivity between MSS without solar collector and TSS was 161% during 12 June 2019 for the rotational speed of 0.5 rpm.
4. Integrating modified solar still with external solar collector lead to enhancement of freshwater productivity at a rotational speed of hollow cylinder of 0.5 rpm by about 292%.
5. It is suggested to perform this new form of the hollow drum with tubular solar still.

In general, the estimated production cost of 1 L of freshwater form TSS is 0.0488 $, and MSS with external solar still is 0.0477 $. Consequently, the results showed an increase in freshwater productivity from modified solar still with external solar collector at a rotational speed of 0.5 rpm.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

CRediT authorship contribution statement

Naseer T. Alwan: Investigation, Methodology, Project administration, Resources, Software. **S.E. Shcheklein:** Conceptualization, Data curation, Formal analysis, Funding acquisition. **Obed M. Ali:** Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing.

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